ELECTRO-OPTIC CHARACTERISTICS OF CdTe AT 3.39 AND 10.6 μ

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The physical characteristics of high resistivity CdTe which are relevant to its use for electro-optic modulation have been investigated at 3.39 and 10.6 μ. The unclamped electro-optic characteristic $n_0^3 r_{41}$ of CdTe was found to be 12×10^{-11} m/V and the absorption coefficient is 0.006 cm^{-1}. Our measurements indicate that CdTe will be a very important material for electro-optic modulation in the infrared.

The electro-optic properties of CdTe at 1.0 μ[1] and at 23.35 and 27.95 μ[2] have been reported previously. We have measured the electro-optic coefficient of high-resistivity CdTe at 3.39 and 10.6 μ and have investigated some of its other properties which are important to its use for electro-optic modulation. The results of these measurements are summarized in Table I, which also includes the relevant characteristics of GaAs, the most commonly used electro-optic material for modulation in the infrared.

We find that $n_0^3 r_{41}$ for CdTe is approximately twice that for GaAs, which would result in a four-fold decrease in the modulation power requirements. The low optical loss of CdTe is of particular importance for applications involving high optical powers, and especially for modulation inside the laser resonator. There is reason to believe that the limiting value of the absorption is even lower than that given, since the difference between the two quoted values is believed to be correlated with the residual scattering losses in the two samples. A meaningful figure of merit from the point of view of high power modulation is the ratio $a/n_0^3 r_{41}$ given in Table I. The quantity is proportional to the fraction of the optical power

Table I. Some modulation-related characteristics of CdTe and GaAs at 10.6 μ.

	CdTe	GaAs
Refractive index n_0	2.6[a]	3.3
$n_0^3 r_{41}$, m/V	$12 \pm 1 \times 10^{-11}$	5.8×10^{-11}
Unclamped electro-optic coefficient r_{41}, m/V	6.8×10^{-12}	1.6×10^{-12}[b]
Absorption coefficient a, cm^{-1}	0.005 ± 0.002 (Sample 1)	0.012[c]–0.02[d]
	0.007 ± 0.002 (Sample 2)	
$a/n_0^3 r_{41}$, 10^{-10} V/m^2	0.5	2
Temperature coefficient of the refractive index $\frac{1}{n}\frac{dn}{dt}$, $°C^{-1}$	$+4.4 \pm 0.3 \times 10^{-5}$	$5.67 \pm 0.34 \times 10^{-5}$[e]
Transmission range, μ	1–30	1–18

[a] Reference 5.
[b] A. Yariv, C. A. Mead, and J. V. Parker, IEEE J. Quantum Electron. **QE-2**, 243 (1966); T. E. Walsh, RCA Rev. **27**, 323 (1966); I. P. Kaminow, IEEE J. Quantum Electron. **QE-4**, 23 (1968).
[c] Reference 4.
[d] Reference 6.
[e] Reference 7.

which is dissipated in the crystal for a given modulation index.

Samples for the measurements were taken from two different boules, one with a resistivity of 10^6 Ω-cm and the other of 10^8 Ω-cm. The material was grown using a modified Bridgman process and is essentially strain free, as indicated by a measured 0.99 extinction coefficient observed between crossed polarizers. In each case, the sample was oriented such that the light propagated in the [110] direction with the optical electric field polarized in the [001] direction and the bias field E applied in the $[\bar{1}10]$ direction. For this orientation in CdTe, which has $\bar{4}3m$ symmetry, the induced phase retardation Γ is a maximum and is given by[3]

$$\Gamma = 2\pi l n_0^3 r_{41} E/\lambda, \tag{1}$$

where l and λ are the sample length and the free space wavelength of the incident radiation. The samples were typically 3.5 mm square in cross section and ranged from 0.7 to 1.5 cm long. Vacuum deposited aluminum, electrolytically applied copper, and silver painted electrodes were used.

Γ was measured experimentally, both by using a dc excitation voltage and by applying an ac field of several frequencies up to 100 kHz and using a quarter-wave plate in series with the sample. In the latter case the transmitted intensity is modulated according to

$$\begin{aligned} I(t)/I_0 &= 1/2[1 + \sin \Gamma(t)] \\ &\approx 1/2[1 + \Gamma(t)], \end{aligned} \tag{2}$$

with the approximation holding when $\Gamma \ll 1$. Within the limits of accuracy of the measurement, we observed the same value for the electro-optic characteristic of CdTe at both 3.39 and 10.6 μ.

The optical losses at 10.6 μ were measured by means of the calorimetric technique described previously.[4] These losses were expected to be lower than in GaAs because the fundamental lattice absorption in CdTe corresponding to the TO(Γ) phonon branch[5] is at 70 μ, so that the absorption at 10.6 μ is probably associated with a seven-phonon process. On the other hand, in GaAs the lattice absorption occurs near $\lambda = 40$ μ so that the stronger four phonon generation is responsible for the absorption.[6]

The coefficient $1/n \cdot dn/dt$ was measured[7,8] by fashioning the crystal into a Fabry-Perot etalon.[9] The magnitude of the coefficient was obtained by measuring the increase in sample temperature necessary to tune the etalon from one pass band to the next, while the sign of the coefficient was obtained by comparing the sign of the change in the etalon transmission caused by changing the temperature and that caused by changing the angle of incidence θ, recalling that for a given transmission the factor $nl \cos \theta$ is constant.

By operating the etalon near its transmission maximum, we obtained a large enhancement of the retardation relative to the values quoted in Table I. A theoretical and experimental description of this effect and an evaluation of its importance in long wavelength infrared modulation will form the subject of a separate publication.

The CdTe samples were grown by Nance Kyle and Robert Walker of the Chemical Physics Department of the Hughes Research Laboratories. The absorption measurements were made by J. Comly of the California Institute of Technology.[10]

[1] O. M. Stafsudd, F. A. Haak, and K. Radisavljevic, Appl. Opt. 6, 1276 (1967).

[2] C. J. Johnson, Proc. IEEE 56, 1719 (1968).

[3] S. Namba, J. Opt. Soc. Am. 51, 76 (1961).

[4] J. Comly, E. Garmire, and A. Yariv, J. Appl. Phys. 38, 4091 (1967). Note: The value of the specific heat of GaAs used in this reference was in error, resulting in an error in a by a factor of 2; therefore, the absorption coefficient should be 0.012 cm^{-1}.

[5] O. G. Lorimor and W. G. Spitzer, J. Appl. Phys. 36, 1841 (1965).

[6] C. A. Klein and R. L. Rudko, Appl. Phys. Letters 13, 129 (1968).

[7] R. Weil, Bull. Am. Phys. Soc. 12, 1657 (1968).

[8] D. G. Peterson and A. Yariv, Appl. Opt. 5, 985 (1966).

[9] This was done by relying on the natural reflectivity (~20%) of the plane, parallel end faces of the sample.

[10] The absorption measurements were supported by the Office of Naval Research and by the Army Research Office—Durham.